

Nonstandard Higgs Boson Decays

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Abstract This review summarizes the motivations for and phenomenological consequences of nonstandard Higgs boson decays, with emphasis on final states containing a pair of non-Standard-Model particles that subsequently decay to Standard Model particles. Typically these non-Standard-Model particles are part of a “hidden” sector, for example a pair of neutral Higgs bosons or a pair of unstable neutralinos. We emphasize that such decays allow for a Higgs substantially below the Standard Model Higgs LEP limit of 114 GeV. This in turn means that the “fine-tuning” problems of many Beyond the Standard Model (BSM) theories, in particular supersymmetric models, can be eliminated while achieving excellent consistency with precision electroweak data which favor a Higgs boson with mass below 100 GeV and standard WW , ZZ , and top couplings.

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1 INTRODUCTION

Understanding the origin of the electroweak symmetry breaking (EWSB) responsible for giving mass to the W and Z gauge bosons of the Standard Model (SM) is the next major step in constructing the ultimate theory of particles and their interactions. The Large Hadron Collider (LHC) is designed specifically to explore the mechanism behind EWSB. In particular, its 14 TeV center of mass energy and greater than 100 fb^{-1} integrated luminosity is such that $WW \rightarrow WW$ scattering can be studied at energies up to about 1 TeV where unitarity would be violated if no new physics associated with EWSB exists.

While many mechanisms for EWSB have been explored, the simplest is the introduction of one or more elementary spin-0 Higgs fields that acquire vacuum expectation values (vevs) and which couple to WW and ZZ . Then, the W and Z gauge bosons acquire a contribution to their mass from each such Higgs field proportional to the strength of the Higgs- WW and Higgs- ZZ coupling times the vev of the Higgs field. The quantum fluctuation of the Higgs field relative to its vev is a spin-0 particle called a Higgs boson. If the corresponding field couples to ZZ and WW then so will the Higgs boson.

While the role of the Higgs vev is to give mass to the W and Z , it is the Feynman diagrams involving the Higgs bosons that prevent unitarity violation in WW scattering provided the Higgs bosons are light enough — roughly below 1 TeV. If the Higgs bosons whose corresponding fields have significant vevs are below about 300 GeV, then WW scattering will remain perturbative at all energies. Furthermore, precision measurements of the properties of W and Z gauge bosons are most consistent if the vev-weighted average of the logarithms

of the Higgs masses is somewhat below $\ln 100$ (GeV units), i.e.

$$\sum_i \frac{v_i^2}{v_{SM}^2} \ln m_{h_i} \leq \ln (100 \text{ GeV}), \quad (1)$$

where $\langle \Phi_j \rangle \equiv v_j$ and $\sum_j v_j^2 = v_{SM}^2 \sim (175 \text{ GeV})^2$ is the square of the vev of the Standard Model Higgs field. Thus, a very attractive possibility is that Higgs bosons with significant WW/ZZ couplings are rather light.

While a 100 GeV Higgs mass is certainly acceptable within the context of the renormalized SM, it requires an enormous cancellation between the bare Higgs mass term in the vev-shifted Lagrangian and the superficially quadratically divergent loop corrections to the mass, especially that arising from the top quark loop. This has led to the idea that there must be new physics below the TeV scale that will regulate these quadratic divergences. For models with elementary Higgs fields, supersymmetry (SUSY) is the earliest proposal for such new physics and remains very attractive. In supersymmetry, the loop corrections containing superparticles come in with opposite sign with respect to those with particles and the quadratic divergences are canceled. If the mass of the stop and the masses of other superparticles are below about 500 GeV, this cancellation will result in a Higgs boson mass in the 100 GeV range more or less automatically. A higher mass for the sparticles would lead to a larger Higgs mass but, as discussed in later sections, would lead to the need to “fine-tune” the soft SUSY breaking parameters at the GUT scale in order that the correct value of the Z boson mass is obtained. The equivalent problem in more general beyond the Standard Model (BSM) theories would be the need to choose parameters at the new physics scale and/or coupling unification scale with great precision in order to obtain the correct value of M_Z .

The fine-tuning problem is closely related to the “little hierarchy problem”

which occurs in a wide variety of BSM theories, including not only supersymmetric models but also Randall-Sundrum theories (1) and Little Higgs theories (2,3). Sometimes referred to as the “LEP Paradox” (4), there is a basic tension existing at present in BSM physics. On the one hand, precision electroweak fits show no need for physics beyond the Standard Model,¹ nor have there been any definitive indications of new particle production at high energy colliders. This suggests the scale of new physics is quite high (greater than 1 TeV). On the other hand, within the context of the Standard Model, electroweak observables require a light Higgs which, as discussed above, is not easy to reconcile with loop corrections to the Higgs mass if the new physics resides above 1 TeV. In these models, it is often difficult to introduce a large quartic coupling for the Higgs to raise its physical mass above the LEP limit, while still protecting its mass term against corrections above the TeV scale.

Thus, the most attractive possibility is a BSM model in which the Higgs bosons with large vevs (and hence large ZZ and WW couplings) have mass of order 100 GeV and new physics resides at scales significantly below 1 TeV while being consistent with current high precision observables. In appropriately constructed BSM models, the latter can be achieved. However, in many models, having Higgs bosons below 100 GeV leads to an inconsistency with the limits from LEP searches for Higgs bosons. Consider first the Standard Model where there is only one Higgs field and one Higgs boson. LEP has placed a limit on the SM Higgs boson, h_{SM} , of $m_{h_{\text{SM}}} > 114.4$ GeV. Except in a few non-generic corners of parameter space, this limit also applies to the lightest CP-even Higgs boson of the Minimal Supersymmetric Model (MSSM) and of many other BSM theories.

¹A possible exception is the 2.2σ discrepancy in $g - 2$ of the muon. (5)

To escape this limit there are basically two possibilities: (i) pushing the Higgs mass to higher values where fine-tuning of parameters becomes an issue or (ii) constructing models where the Higgs bosons with large ZZ coupling have mass at or below 100 GeV but were not detected at LEP by virtue of having nonstandard decays that existing LEP analyses are not sufficiently sensitive to. It is a survey of the unusual decay possibilities that is the focus of this review.

We shall begin by reviewing the motivations for nonstandard Higgs decays in Section 2, discussing model-dependent and model-independent motivations, with particular attention to supersymmetry, especially the next-to-minimal supersymmetric Standard Model (NMSSM). We review the broad set of existing LEP Higgs searches in section 3. There, we emphasize that Higgs bosons of low mass avoid the normal LEP limits only if the primary Higgs decays are into non-Standard-Model particles each of which in turn decays to SM particles. Such decays are termed cascade decays. In Section 4, we specialize to the motivation for nonstandard Higgses from natural electroweak symmetry breaking in supersymmetry theories. In Section 5, we discuss generally the possibilities of extended Higgs sectors; then we focus on the best studied cases in the context of the NMSSM in Section 6. In Section 7, we discuss some implications of nonstandard Higgs physics for B -factories. The LHC implications are discussed in Section 8. Finally, in Section 9 we conclude.

2 MOTIVATION FOR NONSTANDARD HIGGS BOSON DECAYS

The motivation for nonstandard Higgs boson decays comes from two sources. First, a wide variety of theories predict new, neutral states, affording the Higgs

new channels into which it can decay. This common feature motivates us to consider such decays irrespective of anything else. However, naturalness can also be a significant motivation. A theory that is “natural” is one in which the correct Z boson mass is obtained without any significant fine-tuning of the fundamental parameters of the model: for example, the GUT-scale soft SUSY breaking parameters in supersymmetric models.

There is often a tension in theories beyond the Standard Model between naturalness and achieving a Higgs boson mass above the LEP limit. This has been especially well studied within the context of supersymmetry. By allowing the Higgs to decay into new final states, one can have a lighter Higgs, and a more natural theory. Indeed, the recent interest in nonstandard Higgs decays was spurred by the observation that the tension between natural electroweak symmetry breaking in supersymmetric models and not seeing the Higgs boson at LEP can be completely eliminated in models in which $h \rightarrow b\bar{b}$ is not the dominant decay mode of the SM-like Higgs boson (6).

In the SM, there is just one Higgs boson and its dominant decay mode is $h_{\text{SM}} \rightarrow b\bar{b}$ when $m_{h_{\text{SM}}} \lesssim 140$ GeV. Although we have not yet made a definitive observation of this new state, a wide variety of tests at high energy experiments have already constrained its properties. In particular, precision electroweak tests have continually suggested that the Higgs boson is light and accessible at LEP2. The latest fits give an upper bound of 144 GeV at 95% CL with a central value of 76 GeV (7). Compared to the direct search bound of 114.4 GeV, it can be seen that there is some mild tension between these two Higgs bounds. However, as (8) points out, the story is more complicated. Notably, the measured forward-back asymmetry for b quarks (A_{FB}^b) favors a heavy Higgs, but also is the most

discrepant with the Standard Model fit (with a pull of about 3σ). Taking into account most of the data (8), the Standard Model electroweak fit has a poor confidence level of 0.01, whereas leaving out the most discrepant measurements improves the fit to a CL of 0.65. However, then the best fit Higgs mass is 43 GeV, making the indirect Higgs bound more strongly in disagreement with the direct search limit.

New measurements within the Standard Model have continued to support this preference for a light Higgs. In particular, the precise top and W mass measurements from Tevatron Run II have both gone in this direction. The constraint of the top and W mass on the Higgs mass is well known, see e.g. (9). As of right now, the precision electroweak fit is inconsistent with the direct search limit at the 68% CL. This includes fitting A_{FB}^b , so excluding that measurement would increase the discrepancy between the two limits. Thus, even without specifying a particular theory of physics, we see there is some tension for the Standard Model Higgs at present, and this motivates us to consider what possibilities exist for a light Higgs, and in particular, one lighter than the nominal SM limit from LEP.

Furthermore, there were interesting excesses at LEP2 in Higgs searches, which suggest there could be nonstandard Higgs physics. The largest excess (2.3σ) of Higgs-like events at LEP was in the $b\bar{b}$ final state for a reconstructed mass $M_{b\bar{b}} \sim 98$ GeV (10). The number of excess events is roughly 10% of the number of events expected from the Standard Model with a 98 GeV Higgs boson. Thus, this excess cannot be interpreted as the Higgs of the Standard Model or the SM-like Higgs of the MSSM.² However, this excess is a perfect match to the idea

²In the MSSM, this excess can be explained by the lighter CP-even Higgs has highly reduced coupling to ZZ ; see *e.g.* (11). This explanation doesn't remove the fine-tuning problem since it is the heavy CP-even Higgs which is SM-like and has to satisfy the 114 GeV limit. For a

of nonstandard Higgs decays, since the nonstandard decay width reduces the branching ratio to Standard Model modes.

In the Standard Model, the Higgs has strong $O(1)$ couplings to the W, Z and top quark, but quite weak couplings to other fermions. This means that for a Higgs mass that is below threshold for on-shell WW decays, the decay width into standard modes (in particular, $b\bar{b}$) is quite suppressed. A Higgs of mass, *e.g.*, 100 GeV has a decay width into Standard Model particles that is only 2.6 MeV, or about 10^{-5} of its mass. Consequently, the branching ratios to SM particles of such a light Higgs are easily altered by the presence of nonstandard decays; it doesn't take a large Higgs coupling to some new particles for the decay width to these new particles to dominate over the decay width to SM particles; the earliest studies pointing this out of which we are aware are (13–15).

As one, but perhaps the most, relevant example, let us consider a light Higgs with SM-like $b\bar{b}$ coupling and compare the decay width $h \rightarrow b\bar{b}$ to that for $h \rightarrow aa$, where a is a light pseudoscalar Higgs boson. Writing $\mathcal{L} \ni g_{haa} haa$ with $g_{haa} = c \frac{gm_h^2}{2M_W}$ and ignoring phase space suppression, we find

$$\frac{\Gamma(h \rightarrow aa)}{\Gamma(h \rightarrow b\bar{b})} \sim 310 c^2 \left(\frac{m_h}{100 \text{ GeV}} \right)^2. \quad (2)$$

This expression includes QCD corrections to the $b\bar{b}$ width as given in HDECAY (16); these are evaluated for a 100 GeV Higgs and decrease the leading order $\Gamma(h \rightarrow b\bar{b})$ by about 50%. The decay widths are comparable for $c \sim 0.057$ when $m_h = 100 \text{ GeV}$. Values of c at this level or substantially higher (even $c = 1$ is possible) are generic in BSM models containing an extended Higgs sector. Further, both the $h \rightarrow aa$ and $h \rightarrow WW$ decays widths grow as m_h^3 , so that, assuming SM hWW coupling, $\Gamma(h \rightarrow aa) = \frac{1}{2}c^2\Gamma(h \rightarrow WW)$ when neither is

detailed discussion and references, see Ref. (12).

kinematically suppressed.

From a theoretical perspective, many BSM theories have light neutral states such as nonstandard Higgs bosons, axions, neutralinos, sneutrinos, *etc.* which are difficult to detect directly at existing colliders. Typically, the main constraint on such light neutral states arises if they contribute to the invisible Z width. Thus, there are no strong constraints on their masses as long as their coupling to the Z is suppressed. As a result, many of the light states in BSM models can be light enough that a pair of them may appear in the decays of the Higgs boson. And, as discussed above, even a weak coupling of the Higgs boson to these light BSM particles can cause this nonstandard decay to dominate over the standard decay width.

In many cases, the LEP2 constraint on the mass of the Higgs boson is much weaker in the resulting final state than is the case if the Higgs boson decays to either (a) a purely invisible final state or (b) a final state containing just a pair of SM particles; for either final state, the LEP2 data requires that the Higgs mass be greater than 114 GeV if the Higgs ZZ coupling is SM-like. This is because these two final states are avoided if the light states are unstable, resulting in a high multiplicity final state cascade decay with some visible particles. Note that since the cascade is initiated by Higgs decay to just a pair of nonstandard particles, there is no additional phase space suppression relative to a pair of SM particles and the nonstandard pair can easily dominate despite the ultimate final state containing many particles. The importance of cascade decays particularly emerged in early studies of the MSSM (13, 15, 17), $E(6)$ models (18) and the NMSSM (19). These and other models (such as triplet Higgs models and left-right symmetric models) with cascade decays of one Higgs boson to a pair of

lighter Higgs bosons or supersymmetric particles were summarized in the Higgs Hunters Guide (20,21), which contains references to the original work.

In more extreme models, LEP2 constraints are ineffective for even quite light Higgs bosons. One particular example is the early work of (22) in which there are many Higgs fields that mix with one another and share the SM Higgs field vev. In this case, the physical Higgs eigenstates also share the ZZ -Higgs coupling. If the Higgs eigenstates are also spread out in mass, perhaps slightly overlapping within relevant experimental resolutions (the worst case), they could easily have avoided detection at LEP2 even if they have mass significantly below 100 GeV and decay to a pair of SM particles. In fact, however, such models typically have at least modest triple-Higgs couplings and thus many of these multiple Higgs bosons would decay primarily to a pair of lighter Higgs bosons each of which might then decay either to a pair of SM particles or perhaps to a pair of still lighter Higgs bosons. A related model is that of (23) in which many unmixed (and, therefore, stable) Higgs singlet fields are present and couple strongly to the SM Higgs field. The SM Higgs will then decay primarily to pairs of singlet Higgs bosons, yielding a very large SM Higgs width for the invisible final states. Because of the large width, the corresponding signal would have been missed at LEP2 so long as the SM Higgs does not have mass too much below 100 GeV.

To summarize, there is a wide open window for Higgs decays to light unstable states with small coupling to the Z . Indeed, beyond the Standard Model theories having a mass light compared to the WW threshold for Higgs bosons that couple strongly to WW, ZZ will generically have nonstandard Higgs phenomenology. Light states are ubiquitous in BSM theories and could potentially be light enough for the Higgs to decay into a pair of them. Given that the decay width to a pair

of SM particles is so small for such Higgs bosons, the decay into a pair of BSM states can easily dominate even when the relevant coupling is not particularly strong. Thus, the Higgs bosons associated with the Higgs fields that give mass to the W and Z are highly susceptible to having nonstandard Higgs phenomenology. This will be illustrated in greater depth as we discuss some particularly attractive model realizations of such decays.

3 LEP SEARCHES FOR THE HIGGS

Clearly, it is crucial to understand whether decays of a Higgs boson to non-SM particles allow consistency with existing LEP limits when the Higgs has mass below 100 GeV. Although much attention is focused on the SM Higgs search at LEP, there are actually a wide variety of searches which were performed, constraining many scenarios of nonstandard Higgs decays for light ($\lesssim 114.4$ GeV) Higgses. We summarize here these constraints.

The dedicated Higgs searches at LEP2 encompass an impressive array of possible Higgs decay topologies. Since the Higgs is dominantly produced in association with a Z boson, the search topology generally involves both the Higgs and Z decay. The searches give a constraint on the product

$$\xi_{h \rightarrow X}^2 \equiv \frac{\sigma(e^+e^- \rightarrow Zh)}{\sigma(e^+e^- \rightarrow Zh)_{SM}} Br(h \rightarrow X). \quad (3)$$

The cross section σ for Higgs production scales as the coupling g_{ZZh} squared, so the first factor is equivalently the square of the ratio of this Higgs' coupling to the Standard Model value. In Section 2, it was argued that precision electroweak results suggest that the nonstandard Higgs has nearly standard couplings to Standard Model particles, so this factor is close to one.³ The second factor,

³In some cases, the SM ZZ coupling squared is shared among several Higgs bosons. This

$Br(h \rightarrow X)$, is the branching ratio of the Higgs decay in question. Now, we will discuss the relevant LEP2 Higgs searches for our purposes. Most stated mass limits are the 95% CL lower bounds assuming that $\xi_{h \rightarrow X}^2 = 1$.

Standard Model Higgs: For any Higgs that is SM-like in its couplings *and* decays, LEP limits are strongest for the dominant Higgs decays into $b\bar{b}, \tau\bar{\tau}$. LEP combined limits on the SM Higgs (10) require $m_h \geq 114.4$ GeV. This study also includes the strongest limits on $h \rightarrow b\bar{b}, \tau\bar{\tau}$ rates with limits of about 115 GeV if the decay is exclusively into either decay mode.

Two parton hadronic states (aka Flavor-Independent): In this analysis, the two parton decays of a SM-like Higgs were constrained. The analyses use the two parton final state that was least sensitive to the candidate Higgs mass and details of the Z decay. The strongest constraint is the preliminary LEP-wide analysis (24) requiring $m_h \geq 113$ GeV.

Gauge Boson Decays (aka Fermiophobic): This analysis focuses on two gauge boson decays of the Higgs, usually assuming that the Higgs coupling to SM fermions is suppressed. The final states that are considered are WW^*, ZZ^* as well as photons. Assuming SM-like coupling to ZZ^* and WW^* , implying the SM decay width into gauge bosons, there is a limit of $m_h \geq 109.7$ GeV, while decays exclusively to two photons have a limit of $m_h \geq 117$ GeV (25).

Invisible Decays: In this analysis, the Higgs is assumed to have SM-like ZZ coupling but to decay with 100% branching into stable neutral noninteracting

is not typically the case for generic parameter choices for BSM models. Thus, in this section, when we refer to “the Higgs”, we will be presuming that the Higgs has SM-like ZZ and WW couplings, but will allow for the possibility of nonstandard decays.

particles. The most stringent constraints are from an older preliminary LEP-wide analysis with a limit $m_h \geq 114$ GeV, see (26). Since this constraint is so strong, the implication is that a nonstandard Higgs must decay primarily into a state containing at least some visible particles if it is to have mass below 114 GeV.

Cascade Decays: These constraints are relevant for the important nonstandard Higgs decay where the Higgs decays into two secondary particles, such as a pair of scalars ϕ , and those scalars decay into Y (i.e. $h \rightarrow 2\phi \rightarrow 2Y$). OPAL (27) and DELPHI (28) looked at b decays ($Y \equiv b\bar{b}$), while a LEP-wide analysis (29) has constrained both b and τ decays. For $h \rightarrow 2\phi \rightarrow 4b$ the limits are 110 GeV for a Higgs produced with SM strength. For other intermediate scalar decays, $\phi \rightarrow 2g, c\bar{c}, \tau\bar{\tau}$, the best model-independent exclusions are from OPAL's analysis when the mass of the scalar is below $b\bar{b}$ threshold. These limits are given in (30). It will be very important to note that this latter analysis is restricted to Higgs masses in the range 45 – 86 GeV.

Model-Independent Decays: This is the most conservative limit on the Higgs boson. It assumes that the Higgs is produced with a Z boson and looks for electron and muon pairs that reconstruct to a Z mass, while the Higgs decay process is unconstrained. This study was done by OPAL, giving a limit of $m_h \geq 82$ GeV (31).

Notice that these Higgs searches essentially exclude all Higgs decays into a *pair* of Standard Model particles of a single Higgs with SM-like ZZ coupling and mass below about 113 GeV. The only possibilities not mentioned above are Higgs decays into a pair of electrons or muons. However, even though there is no dedicated search of this type, such Higgs decays would give a large enhancement

to charged lepton events at LEP2. Since WW and Ze^+e^- production at LEP2 was accurately measured to be consistent with the Standard Model (32), limits on such decays would presumably be near the kinematic limit. Thus, it is essentially impossible for any Higgs boson (with SM-like ZZ coupling) to have mass much below 114 GeV if it decays entirely into any single mode or combination of modes, each of which contains just a pair of SM particles.

However, this does not rule out Higgs decays into a higher multiplicity state. Take for instance the cascade decay of the Higgs into $4b$. This has a weaker constraint than the $2b$ search, although it only lowers the limit on the Higgs mass to 110 GeV. More drastically, the decay of the Higgs into 4τ allows a Higgs as light as 86 GeV.⁴ This is a substantial weakening of the limit as compared to the di-tau search limit of 115 GeV. Having said this, it does not mean that general high multiplicity decays are completely safe. First of all, the model independent decay search requires that the Higgs be heavier than 82 GeV. Dedicated LEP2 searches to particular decay topologies would of course be more stringent than this. However, absent these dedicated limits, we will give plausible arguments that certain nonstandard decays allow lighter Higgses. Our arguments will be based on applying existing LEP2 analyses to these scenarios. The estimated limits on such Higgs decays obtained in this way should only be taken as a guideline.

⁴OPAL's examination of the 4τ decay cut off the analysis at 86 GeV, so it is not clear what the reach of LEP is for a Higgs decaying in predominantly to 4τ . However, it could reasonably be in the 90-100 GeV range.

3.1 Decay Topologies Consistent With LEP Searches

Before we go into more specific details of specific BSM models, let us review the possibly important topologies and decays which are consistent with the existing data. At the present, there are no strong constraints on decays for Higgses above the LEP kinematical limit, and we shall return to those cases later. We shall begin by focusing on what topologies are allowed in light of the existing search data.

As we have already made clear, *decays of the Higgs into two body SM states are essentially as constrained as the SM Higgs*. This compels us to consider decays into new states. If these states were neutral, stable and weakly interacting, they would contribute to the invisible Higgs search. Thus, to evade the strongest LEP limits, the Higgs must decay to a final state containing at least one unstable particle which does not decay invisibly.

The simplest possible decay process is, $h \rightarrow 2a \rightarrow 4x$, where x is some SM state. $x = b$ is already very constrained, but $x = \tau$ is not constrained if $m_h > 86$ GeV (29), and no explicit limits have been placed on situations where x is a light, unflavored jet for a masses above 10 GeV, although one can reasonably extrapolate limits in the range of 90 GeV from other analyses (33). Naively, it is hard to imagine that cases where $x = e, \mu, \gamma$ are not excluded up to nearly the LEP kinematical limit; however, no analyses have been explicitly performed and the LEP collaborations are not prepared to make an explicit statement.

More complicated decay topologies can arise when there are multiple states below the Higgs mass, for instance a bino and a singlino (which appear in generalized supersymmetric models). Assuming R -parity conservation, such decays are typically characterized by two Standard Model fermions and missing energy. For

instance, a particularly plausible decay mode is $h \rightarrow (\tilde{\chi}_1)\tilde{\chi}_0 \rightarrow (\tilde{\chi}_0 f \bar{f})\tilde{\chi}_0$, where the $\tilde{\chi}_0$ is the LSP. Typically, a single $f\bar{f}$ mode does not dominate, as the decay often includes multiple off-shell sleptons or an off-shell Z -boson. As a result, for plausible branching ratios, such decays are allowed for Higgs masses in the range $90 - 100$ GeV (34).

Most of the above mentioned nonstandard decays arise in the NMSSM and in closely related variants of it. Moreover, the NMSSM is well studied and is the simplest supersymmetric model in which it has been explicitly shown that fine-tuning and naturalness problems can be eliminated when the Higgs boson has mass at or below ~ 100 GeV. Thus, in the next section we turn to a detailed discussion of naturalness in supersymmetric models and in the MSSM in particular. In Section 6, we will explain how fine-tuning can be absent in the NMSSM by virtue of nonstandard Higgs decays allowing $m_h \sim 100$ GeV and then consider the crucial new Higgs signals within the NMSSM as well as its generalizations.

4 NATURAL ELECTROWEAK SYMMETRY BREAKING IN SUPERSYMMETRY

Within supersymmetry, the importance of minimizing fine-tuning provides a particularly strong motivation for nonstandard Higgs decays. Consider first the MSSM. It contains two Higgs doublet fields, H_u and H_d , (with coupling to up type quarks and down type quarks/leptons, respectively). EWSB results in five physical Higgs states: light and heavy CP-even Higgs bosons, h and H , the CP-odd Higgs boson A , and charged Higgs bosons H^\pm . One typically finds that the h is SM-like in its couplings to gauge bosons and fermions. Further, since the

model predicts $m_h < 140$ GeV, $h \rightarrow b\bar{b}$ is then the dominant decay mode.⁵ As a result, the LEP limit of $m_h > 114.4$ GeV applies and, as discussed below, will, in turn, imply a significant fine-tuning problem. It is only by turning to more general supersymmetric models that fine-tuning can be avoided. In more general models such as the NMSSM, the SM-like nature of the lightest CP-even Higgs boson remains a generic feature, but it is not necessarily the case that it dominantly decays to $b\bar{b}$. As we have discussed, due to the small size of the SM-like $hb\bar{b}$ coupling, any new decay modes that are kinematically accessible tend to dominate the Higgs decays and can allow $m_h \leq 100$ GeV to be consistent with LEP limits. For such m_h values, fine-tuning problems can be absent. Phenomenological implications of such a scenario are dramatic. In particular, prospects for detecting the h at the Tevatron and the LHC are greatly modified.

Let us now focus on the issues of naturalness and fine-tuning. For the triggering of EWSB by SUSY breaking to be natural, the superpartners must be near the EW scale. This is because the mass of the Z boson, determined by minimizing the Higgs potential, is related to the supersymmetric Higgs mass parameter μ and the soft SUSY breaking mass squared parameter for H_u , for $\tan\beta \geq 5$, by:

$$\frac{M_Z^2}{2} \simeq -\mu^2(M_Z) - m_{H_u}^2(M_Z). \quad (4)$$

The EW scale value of $m_{H_u}^2$ depends on the boundary conditions of all soft SUSY breaking parameters through renormalization group (RG) evolution. For a given $\tan\beta$, we can solve the RG equations exactly and express the EW values of $m_{H_u}^2$, μ^2 , and consequently M_Z^2 given by Eq. (4), in terms of all GUT-scale parameters;

⁵For discussion of the possibility that H is SM-like or that h and H share the coupling to ZZ and WW see *e.g.* (12) and references there in. Fine-tuning can be ameliorated but not eliminated in such models.

although we consider the GUT-scale as an example, the conclusions do not depend on this choice. For $\tan \beta = 10$, we have:

$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_t^2 - 0.8A_tM_3 + 0.2A_t^2 + \dots, \quad (5)$$

where parameters appearing on the right-hand side are the GUT-scale parameters. Here, M_3 is the $SU(3)$ gaugino mass, A_t is the trilinear stop soft SUSY breaking mixing parameter and for simplicity we have defined $m_t^2 \equiv \frac{1}{2}(m_{t_L}^2 + m_{t_R}^2)$, the latter being the soft SUSY breaking stop mass squared parameters. Other scalar masses and the $U(1)_Y$ and $SU(2)$ gaugino masses, M_1 and M_2 , appear with negligible coefficients and we neglect them in our discussion. The coefficients in this expression depend weakly on $\tan \beta$ and on $\log(M_{\text{GUT}}/M_Z)$. We can express the EW scale values of the stop mass squared, gluino mass and top trilinear coupling in a similar way; for $\tan \beta = 10$ we have:

$$m_t^2(M_Z) \simeq 5.0M_3^2 + 0.6m_t^2 + 0.2A_tM_3 \quad (6)$$

$$M_3(M_Z) \simeq 3M_3 \quad (7)$$

$$A_t(M_Z) \simeq -2.3M_3 + 0.2A_t. \quad (8)$$

From Eqs. (5), (6) and (7), we see the usual expectation from SUSY,

$$M_Z \simeq m_{\tilde{t}_{1,2}} \simeq m_{\tilde{g}}, \quad (9)$$

when all the soft SUSY breaking parameters are comparable. Furthermore, neglecting terms proportional to A_t in Eqs. (8) and (6) we find that a typical stop mixing is $A_t(M_Z)/m_{\tilde{t}}(M_Z) \lesssim 1.0$. This result has an important implication for the Higgs mass.

The mass of the h is approximately given as:

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \left\{ \log \frac{m_{\tilde{t}}^2(M_Z)}{m_t^2} + \frac{A_t^2(M_Z)}{m_{\tilde{t}}^2(M_Z)} \left(1 - \frac{A_t^2(M_Z)}{12m_{\tilde{t}}^2(M_Z)} \right) \right\}. \quad (10)$$

where the first term is the tree level result and the second term is the dominant one loop correction (35–38). At tree level, $m_h \leq M_Z \simeq 91$ GeV. It can be increased beyond this value either by increasing the mixing in the stop sector, $A_t(M_Z)/m_{\tilde{t}}(M_Z)$, or by increasing the stop mass, $m_{\tilde{t}}(M_Z)$. As we have learned, the typical mixing in the stop sector achieved as a result of RG evolution from a large range of high scale boundary conditions is $A_t(M_Z)/m_{\tilde{t}}(M_Z) \lesssim 1.0$. With this typical mixing, we obtain the typical Higgs mass, $m_h \simeq 100$ GeV. In order to push the Higgs mass above the LEP limit, 114.4 GeV, assuming the typical mixing, the stop masses have to be $\gtrsim 1$ TeV.^{6 7}

The need for 1 TeV stops is in direct contradiction with the usual expectation from SUSY, Eq. (9). The hierarchy between the scale where SUSY is expected and the scale to which it is pushed by the limit on the Higgs mass requires a precise cancellation, at better than 1% precision, between the soft SUSY breaking terms and the μ term appearing on the right-hand side of Eq. (5) in order to recover the correct value of the Z mass. This is the explicit realization of the fine-tuning

⁶The Higgs mass is maximized for $|A_t(M_Z)/m_{\tilde{t}}(M_Z)| \simeq 2$, which corresponds to the maximal mixing scenario. In this case, $m_{\tilde{t}}(M_Z)$ can be as small as ~ 300 GeV without violating the bound on m_h from LEP. However it is not trivial to achieve the maximal mixing scenario in models. For more details see, *e.g.*, the discussion in Refs. (39,40).

⁷In models beyond the MSSM, with extended Higgs sectors or extended gauge symmetries, the tree level prediction for the Higgs mass can be increased, see Refs. (41,42) and references therein. This increase is not automatic and typically requires nontrivial assumptions. For example, in the NMSSM (as defined in Sec. 3) assuming perturbativity up to the GUT scale, the tree level prediction for the Higgs mass can be increased only by a small amount.

problem in the MSSM and, as described in the introduction, is closely related to the little hierarchy problem.

The solution to the fine-tuning problem in models in which the SM-like Higgs decays dominantly to non-SM particles is straightforward. If the $h \rightarrow b\bar{b}$ decay mode is not dominant the Higgs boson does not need to be heavier than 114 GeV, it can be as light as the typical Higgs mass or even lighter depending on the experimental limits placed on the dominant decay mode. If the strongest limit is ≤ 100 GeV, there is no need for large superpartner masses and superpartners can be as light as current experimental limits allow. In Section 3, we reviewed the experimental limits on the mass of the SM-like Higgs boson in various decay modes. Quite surprisingly, only if the Higgs decays primarily to two or four bottom quarks, two jets, two taus or to an invisible channel (such as two stable LSPs), is the LEP limit on m_h above 100 GeV. Most other decay topologies have not been studied directly, and applications of other searches (e.g., the sensitivity of the flavor-independent two jet search to the general four jet topology) typically imply weak limits.⁸ Moreover, it is reasonable to take a very conservative approach in which one does not extrapolate LEP limits beyond their explicit analyzed topology.

Regardless, LEP limits on m_h for other decay modes are generally below 90 GeV and would therefore not place a constraint on superpartner masses. Since $m_h \sim 90 - 100$ GeV is the generic prediction for supersymmetric models in which

⁸We are assuming that the Higgs is produced with standard strength. A four bottom quark decay for a Higgs which is strongly mixed as in (43) may be allowed for Higgs mass below 100 GeV within the existing constraints. Even so, a state lighter than ~ 105 GeV which decays to four bottom quarks cannot have a coupling larger than 40% of standard-model strength. Such models represent a different approach than we principally consider here.

there is no fine tuning, those supersymmetric models where these alternate decay modes are dominant automatically provide a solution to the fine-tuning problem.⁹

Besides alleviating or completely removing the fine-tuning problem the possibility of modified Higgs decays is independently supported experimentally. As mentioned in Section 2, the largest Higgs excess suggested a nonstandard Higgs of mass 98 GeV, that only decayed 10% of the time to Standard Model decay modes. As we have discussed, from natural EWSB we expect the SM-like h to have mass very near 100 GeV, and this is possible in any model where the SM-like Higgs boson decays mainly in a mode for which the LEP limits on m_h are below 100 GeV, such as those mentioned earlier for which LEP limits run out at 90 GeV.¹⁰ The $h \rightarrow b\bar{b}$ decay mode will still be present, but with reduced branching ratio. Any $\text{Br}(h \rightarrow b\bar{b}) \lesssim 30\%$ is consistent with experimental limits for $m_h \sim 100$ GeV. Further, $\text{Br}(h \rightarrow b\bar{b}) \sim 10\%$ with $m_h \sim 100$ GeV provides a perfect explanation of the excess. This interpretation of the excess was first made in the NMSSM with the $h \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ mode being dominant (47), but it clearly applies to a wide variety of models.

Within the MSSM context, there is one scenario worth mentioning that can alleviate fine-tuning. For example, for $\tan\beta \sim 10$, $\bar{m}_t(M_Z) \sim 300$ GeV and $A_t(M_Z) \sim -400$ GeV, fine-tuning is moderate ($\sim 6\%$) and $m_h \sim 95 - 100$ GeV, thereby providing a contribution to the ~ 98 GeV LEP excess observed (10) at

⁹In specific models, avoiding the fine-tuning problem might require another tuning of parameters in order to make an alternative decay mode for the Higgs boson dominant, see, *e.g.*, Ref. (44,45) for the discussion of these issues in the NMSSM.

¹⁰Another possibility would be that a weakly mixed state existed at 98 GeV but the dominant state coupling to the Z was above the LEP bound. (See, *e.g.*, (46).)

LEP. In this case, LEP limits are evaded by virtue of substantial Higgs mixing leading to greatly reduced hZZ coupling; the HZZ coupling is large but m_H is slightly above the LEP limit of 114.4 GeV.¹¹ In fact, for $\tan\beta \sim 20$ one can simultaneously fit the ~ 98 GeV and ~ 116 GeV LEP excesses (11, 12, 46). These scenarios, however, require highly nongeneric boundary conditions at the GUT scale and are clearly scenarios characterized by nearly maximal mixing in the stop sector. Another scenario is that in which one allows large CP violation in the Higgs sector. Then, the physical MSSM Higgs states will be mixtures of the CP-even h and H and the CP-odd A ; let us label the 3 resulting eigenstates as $H_{1,2,3}$. It is possible to arrange $2m_{H_1} < m_{H_2}$ with the H_2ZZ coupling near maximal and $m_{H_2} \leq 100$ GeV (48). This can be consistent with LEP limits if the $H_2 \rightarrow H_1 H_1$ cascade decay is dominant and $m_{H_2} < 2m_b$. Whether or not this scenario is fine-tuned has not been studied, but one can speculate that the low mass of the H_2 would imply reduced fine-tuning. However, for m_{H_1} sufficiently below the Upsilon mass, the rate for $\Upsilon \rightarrow \gamma H_1$ would typically be large and inconsistent with limits (49) from B factories. This is because the H_1 is part of a doublet (unlike the NMSSM where the a_1 is mainly singlet) and, since the H_2 is the SM-like Higgs, the H_1 (and H_3) will have $\tan\beta$ -enhanced coupling to $b\bar{b}$.

In summary, it is only models with nonstandard Higgs decays that can completely avoid the fine-tuning problem. They allow the Higgs boson mass to be the $m_h \sim 100$ GeV value predicted from natural EWSB while at the same time the now subdominant decay mode, $h \rightarrow b\bar{b}$, with $\sim 10\%$ branching ratio can explain the largest excess of Higgs-like events at LEP at $M_{b\bar{b}} \sim 98$ GeV. A SM-like h

¹¹Without such mixing, the $m_h > 114$ GeV LEP limit applies and at least 3% fine-tuning is necessary.

with $m_h \sim 100$ GeV is also nicely consistent with precision electroweak data.

5 HIGGS AS A LINK TO NEW SECTORS

The Higgs field plays a unique role in the Standard Model in that $h^\dagger h$ is a complete Lorentz and gauge singlet, but is only dimension two. As a consequence, it can couple to hidden sector scalar fields (real or complex, the latter implying the presence of both scalar and pseudoscalar mass eigenstates) through the renormalizable operator $\phi^* \phi h^\dagger h$ or through the dimension three trilinear interaction $\phi h^\dagger h + h.c.$. The latter can be eliminated by requiring a symmetry under $\phi \rightarrow -\phi$. If we presume that the trilinear term is absent then it is still the case that couplings of the type $h\phi\phi$ will be generated for the mass eigenstates when the h field acquires a vev. Similarly, the h can couple to (vector-like) SM singlet fermions through the dimension five operator $\bar{n} n h^\dagger h$. Because the width of the Higgs eigenstate (also denoted h) is small for $m_h < 160$ GeV, decays to a pair of ϕ 's or n 's can dominate the decay of the h , in the former case with a perturbative dimensionless coupling and in the latter case if the operator is suppressed by a scale near the weak scale. We review here some of the possibilities arising from these operators. Both of the above possibilities arise quite simply in the NMSSM, but we first consider them in a general context.

There are many possible final signals in the case of $h \rightarrow \phi\phi$ decays. The various cases depend upon whether ϕ acquires a vev or not and on whether the ϕ couples to a new heavy BSM sector. If the ϕ field does not acquire a vev and does not couple to some new BSM sector, then the ϕ mass eigenstate will be absolutely stable. If the h width remains narrow for such decays, then LEP2 limits on an invisible h , requiring $m_h \geq 115$ GeV will apply. However, this limit can be evaded

if the invisible width is very large. Models ¹² in which this can happen include the case of a large number of strongly coupled scalars (23) and, for some extreme parameter choices, the recent unparticle models (which can be deconstructed in terms of a “continuum” of stable invisible scalars, a subcase of the former class of models) (50).

If the purely singlet scalar couples to the mass of some heavy BSM fermions (*i.e.* $(\lambda\phi + M)\bar{\psi}\psi$), then h decays to four photons or four jets can dominate the Higgs width (51,52). The four photon channel can also be dominant in NMSSM models (53) where $h \rightarrow aa$ and the a is purely singlet and the $a\gamma\gamma$ coupling arises from virtual loops containing supersymmetric gauginos and higgsinos. The four photon mode would have been easily discoverable at LEP were it below the kinematic bound while the four gluon decay would have been a challenge (52). If there are multiple states below the Higgs mass, then very complicated decays, such as $h \rightarrow 6f$ or $h \rightarrow 8f$ can arise, where f can represent various fermions.

A purely singlet scalar can in fact be very long lived if it decays through loop-suppressed or non-renormalizable operators (52,54,55). This allows decays of the Higgs with significantly displaced vertices which may be an intriguing avenue to search for new physics like that of “Hidden Valleys” (55). However, such decays would likely have been noticed had they been the dominant decay mode at LEP.

Let us now discuss the cases in which the the singlet scalar field acquires a vev or there is an $h^\dagger h\phi + h.c.$ component in the Lagrangian. In these cases, the above discussion does not apply. The light singlet state will typically mix with the non-singlet Higgs boson(s) and thereby acquire a significant coupling to

¹²We do not consider invisible decay modes related to graviscalars and so forth that arise in theories with extra dimensions.

SM particles, especially the light fermions. Thus, the cascade decays can arise, as described earlier, and reduce the fine-tuning. For very light singlet states, most of the phenomenology is independent of the potential (56), while at heavier masses there is more dependence.

However, without considering specific decays, the mixing alone can influence fine-tuning in two separate ways. First, the Higgs mixing can push up the mass of the heavy mass eigenstate, but at the cost of producing the light state via Higgsstrahlung. At tree level, such mixing does little to alleviate fine-tuning, but with loop effects included, the reduction in fine-tuning can be significant (57). More common is the reduction in fine-tuning due to the fact that a light SM-like Higgs can decay to a pair of still lighter Higgses in such models, thereby allowing the SM-like Higgs to have mass ≤ 100 GeV. As we shall discuss in Section 8, this scenario will also make Higgs discovery at the LHC quite challenging. As one increases the number of states with which the h field can mix (including now both doublets and singlets in general), the primary Higgs field (or fields) that couple to the Z can be spread out among many mass eigenstates. This will make discovery difficult due to the fact that such a model allows a multitude of Higgs to Higgs pair decays, a reduction in the production rate for any one Higgs boson, and an overlapping of the peaks for the individual states in any given detection channel. In particular, these effects can make LHC Higgs detection essentially impossible (22, 58, 59). However, detection at a future linear collider will be possible in the $e^+e^- \rightarrow Z + X$ channel provided sufficient integrated luminosity is available (22).

If the singlet field acquires a vev and yet parameters are chosen so that there is no mixing between the singlet ϕ particle state and the doublet Higgs states, one must again consider whether or not the four photon and other highly suppressed

decay modes of the SM-like Higgs could be dominant. An example is provided by the NMSSM. There, aside from the loop induced $a\gamma\gamma$ coupling considered in (53), supersymmetric particle loops (for example, a loop containing a \tilde{b} and a gluino) also induce $ab\bar{b}$ couplings (60). The latter can be up to one half of SM-like strength (*i.e.* like $h_{\text{SM}}b\bar{b}$ but with an extra γ_5 in the coupling Lagrangian) for very high values of $\tan\beta \sim 50$ and moderate superparticle masses. This is more than likely to swamp the loop-induced $a\gamma\gamma$ couplings in the NMSSM. Generically, even for a purely singlet a , dominance of $a \rightarrow \gamma\gamma$ over $a \rightarrow b\bar{b}$ will only be the case if $\tan\beta$ is small. More generally, if the BSM sector, whose loops give rise to a singlet-2photon coupling, contains any non-SM-singlet fields, one can expect important singlet- $b\bar{b}$ couplings associated with loops of the latter fields.

If the additional scalar is charged under some new gauge symmetry, a strongly mixed Higgs can decay into new gauge bosons (61). However, in order for this to dominate the decay, the mass eigenstate must be significantly mixed ($\sin^2\theta \sim 0.5$).

In the case of BSM fermions dominating the Higgs decay, Higgs decays to right handed neutrinos are an interesting possibility (62, 63). If left-handed neutrinos are involved, decays to different fermions, *i.e.*, $h \rightarrow \psi_1\psi_2$ are possible (34, 64). Such decays with both visible and missing energy are also capable of evading Higgs search limits, as well as other new physics searches (34). Such states could also be neutralinos in the NMSSM, in addition to neutrinos.

In the above discussion, we noted the generic possibility of coupling the doublet Higgs structure $h^\dagger h$ to a SM singlet operator. In fact, in supersymmetry such coupling has a very compelling motivation as an extension of the MSSM. The content of the MSSM in the matter and gauge sectors is fixed by requiring a

superpartner for each known particle of definite helicity. In contrast, the choice of a two doublet Higgs sector is made purely on the basis of minimality arguments (absence of anomalies and the need to give mass to both up and down type quarks) and this choice gives rise to the famous μ -problem. Namely, phenomenology requires a term of the form $\mu \hat{H}_u \hat{H}_d$ ¹³ in the superpotential with μ being a term with dimensions of mass with a value somewhere between about 150 GeV and 1 TeV, as opposed to the natural values of 0 or M_{GUT} . Ideally, one would have no dimensionful parameters in the superpotential, all dimensionful parameters being confined to the soft SUSY breaking potential.

A particularly appealing extension of the MSSM which solves the μ problem is the introduction of a completely new sector of particles which are singlets under the SM gauge symmetry. As such, this extra (E) sector would not spoil any of the virtues of the MSSM, including the possibility of gauge coupling unification and matter particles fitting into complete GUT multiplets. In addition, E -sector particles that either do not mix or have small mixing with SM particles would have easily escaped direct detection. Of course, if this E -sector is completely decoupled from the SM then it plays no role in particle physics phenomenology at accelerators. Much more interesting is the possibility that this sector couples to the MSSM through the Higgs fields. In particular, the E -sector can couple to the SM-singlet $\hat{H}_u \hat{H}_d$ form appearing in the MSSM μ term in many ways, including a renormalizable term (with dimensionless coupling) of form $\lambda \hat{E} \hat{H}_u \hat{H}_d$. When the scalar component of the singlet superfield \hat{E} acquires a vev, $\langle E \rangle = x$ (as a result of SUSY breaking) an effective μ value, $\mu_{\text{eff}} = \lambda x$, is generated.

Such couplings would have a negligible effect on the phenomenology involving SM

¹³Hatted fields denote superfields while unhatted fields are normal fields.

matter particles, whereas they can dramatically alter Higgs physics. In particular, the particle couplings generated allow the lightest CP-even Higgs boson h to decay into two of the particles associated with the E -fields (E -particles) if the E -particles are light enough, and these $h \rightarrow EE$ decays can be dominant for even rather modest $\hat{E}\hat{H}_u\hat{H}_d$ coupling strength.

The implications for Higgs discovery follow some of the patterns discussed above. In particular, when h decays to two lighter E -particles are dominant, the strategy for Higgs discovery will depend on the way the E -particles appearing in the decays of the h themselves decay. The latter might decay predominantly into other stable E -particles, in which case the MSSM-like h decays mainly invisibly. More typically, however, the E -particles mix with the SM particles via the couplings between the MSSM and E -sector. In particular, couplings between E -bosons and the MSSM Higgs fields are generically present and imply that the Higgs mass eigenstates are mixed. In this case, the mostly E -particle light Higgses will decay into $b\bar{b}$, $\tau^+\tau^-$ or other quarks or leptons depending on the model. Although E -particles would have small direct production cross sections and it would be difficult to detect them directly, their presence would be manifest through the dominant Higgs decay modes being $h \rightarrow 4f$, where $4f$ symbolically means four SM particles, *e.g.* $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $\tau^+\tau^-\tau^+\tau^-$, 4γ and so on. The situation can be even more complicated if the h decays to E -particles that themselves decay into other E -particles which in turn finally decay to SM particles. In such a case, the SM-like Higgs would effectively decay into $8f$.

Let us finally note that the presence of a singlet in the potential can lead to modifications in the early universe cosmology. In particular, it allows the possibility of a first-order phase transition (65–67), which can arise consistent

with LEP experiments.

6 CASCADE DECAYS TO SCALARS IN THE NMSSM

The cascade decay scenario described in Sections 2, 3 and 5 already occurs in the simplest extension of the MSSM, the next-to-minimal supersymmetric Standard Model (NMSSM) which adds only one singlet chiral superfield, \hat{S} to the MSSM. Phenomenologically similar scenarios arise naturally in theories with additional $U(1)$'s (68–70). The NMSSM particle content differs from the MSSM by the addition of one CP-even and one CP-odd state in the neutral Higgs sector (assuming CP conservation), and one additional neutralino. We will follow the conventions of (71). Apart from the usual quark and lepton Yukawa couplings, the scale invariant superpotential is

$$\lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 \quad (11)$$

depending on two dimensionless couplings λ and κ beyond the MSSM. The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3. \quad (12)$$

The final two input parameters are

$$\tan \beta = h_u/h_d, \quad \mu_{\text{eff}} = \lambda s, \quad (13)$$

where $h_u \equiv \langle H_u \rangle$, $h_d \equiv \langle H_d \rangle$ and $s \equiv \langle S \rangle$. These, along with M_Z , can be viewed as determining the three SUSY breaking masses squared for H_u , H_d and S (denoted $m_{H_u}^2$, $m_{H_d}^2$ and m_S^2) through the three minimization equations of the scalar potential. Thus, as compared to the three independent parameters needed in the MSSM context (often chosen as μ , $\tan \beta$ and M_A), the Higgs sector of the NMSSM is described by the six parameters

$$\lambda, \kappa, A_\lambda, A_\kappa, \tan \beta, \mu_{\text{eff}}. \quad (14)$$

We will choose sign conventions for the fields such that λ and $\tan \beta$ are positive, while κ , A_λ , A_κ and μ_{eff} should be allowed to have either sign. In addition, values must be input for the gaugino masses and for the soft terms related to the (third generation) squarks and sleptons (especially $m_{t_L}^2$, $m_{t_R}^2$ and A_t) that contribute to the radiative corrections in the Higgs sector and to the Higgs decay widths.

Of all the possible new phenomena the additional Higgses in the NMSSM can lead to, perhaps the most intriguing one is the possibility of the lightest CP-even Higgs decaying into a pair of the two lightest CP-odd Higgses, $h_1 \rightarrow a_1 a_1$, where the latter are mostly singlets (6,40,47,51,72). Precisely this scenario can eliminate the fine-tuning of EWSB in the NMSSM for $m_{h_1} \sim 100$ GeV (6,40). If $\text{Br}(h_1 \rightarrow a_1 a_1) > 0.7$ and $m_{a_1} < 2m_b$, the usual LEP limit on the Higgs boson mass does not apply and the SUSY spectrum can be arbitrarily light, perhaps just above the experimental bounds and certainly light enough for natural EWSB. In addition, without any further ingredients this scenario can completely explain the excess of Higgs-like events in the $b\bar{b}$ channel at $M_{b\bar{b}} \simeq 98$ GeV (47). Finally, the above a_1 scenario is not itself fine-tuned. Starting from A_κ and A_λ values at the GUT scale that are small (and therefore close to a $U(1)_R$ symmetry limit of the potential), the RG equations yield A_κ and A_λ values at scale M_Z that generically result in $\text{Br}(h_1 \rightarrow a_1 a_1) > 0.7$ and $m_{a_1} < 2m_b$ with some preference for $m_{a_1} > 2m_\tau$ (45). In addition, M_Z -scale values for the soft SUSY breaking parameters that correspond to there being no electroweak fine-tuning, imply values of $m_{H_u}^2$, $m_{H_d}^2$ and m_S^2 at the GUT scale that are all relatively small (47). That is, the preferred GUT-scale boundary conditions for the NMSSM are close to the no-scale type boundary conditions where many of the soft SUSY breaking parameters are near zero.

Higgs signals at colliders of all types are dramatically different in the NMSSM models that have no fine-tuning. One must look for $h \rightarrow a_1 a_1 \rightarrow 4\tau$ or $4j$ (somewhat less preferred because of a need to tune A_κ and A_λ). We discuss collider implications in the following sections.

7 LIGHT HIGGSSES AT B FACTORIES

We have seen that a particularly generic way in which a SM-like Higgs with $m_h \sim 100$ GeV can escape LEP limits on the $h \rightarrow b\bar{b}$ and $h \rightarrow b\bar{b}b\bar{b}$ channels, is for the h to decay primarily to two E -bosons which have mass below $2m_b$. The NMSSM scenario of $h_1 \rightarrow a_1 a_1 \rightarrow 4\tau$ is just one example of this generic possibility. However, there is an interesting requirement within the NMSSM scenario that we have not yet mentioned. Namely, $\text{Br}(h_1 \rightarrow a_1 a_1)$ is only large enough to escape LEP limits if the a_1 is not purely singlet (45). There must be some mixing of the CP-odd singlet with the MSSM-like CP-odd Higgs that is a residual from the two doublets. Defining

$$a_1 \equiv \cos \theta_A A_{MSSM} + \sin \theta_A A_S, \quad (15)$$

where A_{MSSM} is the MSSM-doublet CP-odd Higgs and A_S is the CP-odd (imaginary) component of the complex S scalar field, one finds (at $\tan \beta = 10$ for example) that $|\cos \theta_A| \gtrsim 0.06$ is required for $\text{Br}(h_1 \rightarrow a_1 a_1) > 0.7$. The $a_1 b\bar{b}$ coupling, given by $\cos \theta_A \tan \beta \frac{m_b}{v} \bar{b} i \gamma_5 b a_1$, then has a lower bound that is not so far from being SM-like in strength. Further, a light a_1 with the required properties is most naturally obtained after RG evolution of the relevant parameters from GUT-scale boundary conditions when $|\cos \theta_A|$ is near its lower bound, $|\cos \theta_A| \sim 0.1$.

The lower bound on the $a_1 b\bar{b}$ coupling has crucial consequences at B factories

(73,74). In the NMSSM, one finds (73) that for any given m_{a_1} below M_Υ (where Υ denotes the $1S$, $2S$ or $3S$ state) there is a lower bound on $\text{Br}(\Upsilon \rightarrow \gamma a_1)$. Not surprisingly, this lower bound is quite small. For example, to probe m_{a_1} values as high as 9.2 GeV in $\Upsilon(1S)$ decays (such an m_{a_1} being within the preferred $m_{a_1} > 2m_\tau$ range but still leaving some phase space for $\Upsilon(1S) \rightarrow \gamma a_1$ decay), one needs to be sensitive at B factories to $\text{Br}(\Upsilon \rightarrow \gamma a_1 \rightarrow \gamma \tau^+ \tau^-)$ down to $\sim 10^{-7}$ for full coverage of the possible scenarios. Reaching this level is a challenge, but not necessarily impossible using dedicated runs on one of the Υ resonances. Search for non-universality (enhancement of the $\tau^+ \tau^-$ final state) in Υ decays to leptons without directly tagging the photon may also be a useful approach (74).

In more general E -sector scenarios, to have a SM-like h with $m_h \sim 100$ GeV again requires that there be one or more E -bosons with mass below $2m_b$ and the cumulative branching ratio for h decay to these states must be $\gtrsim 0.7$. It is quite likely that some of these states will have reasonable coupling to $b\bar{b}$ and mass low enough to yield a potentially measurable rate for Υ decay to photon plus E -boson, with E -boson decay to $\tau^+ \tau^-$ being more likely than decay to the much more difficult jj final state.

Such searches have great importance given the fact that Υ decays may be the only way prior to the construction of a linear collider to obtain confirmation of the existence of E -bosons that is independent of their hoped for observation at the LHC in h decays. Indeed, generally speaking some light E -bosons might appear in Υ decays that do not appear in h decays!

8 IMPLICATIONS FOR THE LHC

The nonstandard cascade Higgs decay scenario has many interesting LHC implications. Earlier studies have considered whether or not a scalar discovered at the LHC is, in fact, the “Higgs” (75). In the present situation, we are interested in cases where new, possibly unexpected decays have arisen, and the consequences for experimental searches. In this review, we attempt to summarize two aspects of this phenomenology. For simplicity, we presume the model predicts one and only one SM-like Higgs boson and we will refer to it as the “Higgs”. The first aspect is the changes in Higgs phenomenology. One primary implication for the Higgs is that the Standard Model decays are subdominant, rendering the LHC Standard Model Higgs searches less effective. In this regard, it is useful to consider if the nonstandard Higgs decays will lead to a viable Higgs signal. However, it is also interesting to discuss potential model-dependent effects outside of Higgs physics, since such effects combine with the Higgs as a window into new physics. The example we will discuss are changes in the decays of supersymmetric partners of the Standard Model. This suggests that a nonstandard Higgs decay could be accompanied by nonstandard superpartner decays, giving correlated evidence for this model.

In some regions of parameter space, the intermediate particles facilitating the Higgs cascade decay can have highly displaced vertices. In this case, the LHCb detector, with its superior ability to trigger on displaced vertices, can have a greater reach for both Higgs and superpartner decays. Thus, it is even possible that LHCb will be the first LHC experiment to discover this new physics.

8.1 Higgs

The nonstandard Higgs scenario unambiguously predicts changes in the phenomenology of the SM-like Higgs boson of the model. At the LHC, the immediate impact is the weakening of Higgs searches that depend on the Standard Model decay modes. A light Higgs near the LEP2 bound is already a difficult region for the LHC to probe. Instead of depending on the dominant decay of the Higgs to b quarks, the experiments have focused on di-photon Higgs decay and the di-tau decay for a vector boson fusion (VBF) produced Higgs. Both of these searches are statistics limited, so any suppression of the Standard Model decay branching ratio increases the required integrated luminosity for discovery. Naively, the increase in required luminosity is a factor of $1/\text{Br}(h \rightarrow SM)^2$ more. This factor is naive as the searches can become more efficient as the experiment runs, but also the backgrounds can change as the experiment moves to design luminosity. At any rate, for a nonstandard Higgs that is 100 GeV in mass, the Standard Model LEP search determines that the Standard Model branching ratio is at most 25%. Thus, the required integrated luminosity goes up by a factor of at least 16. Extrapolating the numbers shown in the CMS TDR (76), an integrated luminosity $\gtrsim 16 * 25 \text{ fb}^{-1} = 400 \text{ fb}^{-1}$ is needed for discovery, a significant amount of luminosity. In the NMSSM context, a more typical $\text{Br}(h \rightarrow SM)$ is ~ 0.1 , implying a need to increase the luminosity by a factor of roughly 100, as would only be achievable at the SLHC (assuming no change in the signal to background ratio — in fact, S/B will decrease because of the huge number of multiple interactions). Therefore, in order to maintain the reach for Higgs discovery it is important to consider whether the nonstandard Higgs decays can provide a viable Higgs signal.

We focus on the case where there is a SM-like Higgs of the extended model.

Since it couples to Standard Model particles with normal strength, its production cross sections are unmodified. So, to determine the Higgs signal topology we need only specify the nonstandard decay. Before proceeding, it is useful to consider the advantages LHC has over LEP2 to motivate the LHC search strategies. As a hadron collider, LHC has higher integrated luminosity and production cross sections than LEP2 and thus will produce far more of the SM-like Higgses. This allows the LHC to look for the rarer clean decay modes that are not swamped by QCD backgrounds. Indeed, this is the story for the Standard Model Higgs. LEP2 had to look for the dominant decays of $b\bar{b}$ and $\tau\bar{\tau}$, while the LHC instead searches for $\gamma\gamma$ and for $\tau\bar{\tau}$ in vector boson fusion.

8.1.1 HIGGS DECAYS TO SCALARS Higgs decays to a pair of scalars or pseudoscalars (we will use the notation a in our discussion) is the best known nonstandard Higgs phenomenology, having been searched for at LEP2 in the CP-violating MSSM and studied extensively in the NMSSM. In these SUSY scenarios, an a with $m_a > 2m_b$ decays with branching ratios similar to the SM Higgs boson and thus $a \rightarrow b\bar{b}$ decays are dominant with $a \rightarrow \tau\bar{\tau}$ being subdominant.

The dominant decay mode of $h \rightarrow aa \rightarrow 4b$ has strong constraints from LEP2 which require the Higgs mass to be above 110 GeV. Still, it is interesting to see if this decay is capable of being seen above the QCD background at the LHC for such heavy Higgses. In recent papers (77,78), such Higgs decays were studied at Tevatron and LHC. These analyses focused on Higgses produced in association with a W boson and looked at the topology of $4jl\nu$, requiring three or four b -tagged jets. For a 120 GeV Higgs, Ref. (78) finds that 5σ discovery at the LHC requires about 30 fb^{-1} , but is highly reliant on b -tagging efficiencies of 50% at $p_T \sim 15 \text{ GeV}$. Such a high efficiency at this transverse momentum may be

difficult to achieve at the LHC; if this tagging efficiency only holds for transverse momenta greater than 30 GeV, the necessary luminosity goes to 80 fb^{-1} . As one extrapolates to lighter Higgses, these issues will become more important, further increasing the luminosity required. Their work also studied the $2b2\tau$ mode and found that it's prospects were not as promising. For older work on the $4b$ and $2b2\tau$ modes, see (79–84).

If the a mass is below the $b\bar{b}$ threshold ($\sim 12 \text{ GeV}$), the dominant Higgs decay is into 4τ and was only weakly constrained at LEP2. Thus, at the LHC, it is important to analyze the ideal $m_h \sim 100 \text{ GeV}$ scenario in the $h \rightarrow 4\tau$ final state. The two most promising production possibilities are vector boson fusion and diffractive Higgs production. In VBF, one looks for $WW \rightarrow h \rightarrow 4\tau$, with tagging of the forward jets emitting the W 's in order to isolate the signal. Studies of this mode have begun. In diffractive Higgs production, one looks for a special class of events with protons appearing in specially designed detectors and very little additional activity in the final state. In a recent paper (85), it is claimed that by using a track-based analysis in which all events with more than 6 tracks in the central region are discarded, a viable signal is possible after accumulating 300 fb^{-1} of integrated luminosity. This type of track-based approach may also prove key to extracting a viable signal in the VBF fusion channel. There is also an older analysis, looking for $h \rightarrow 4\tau$ at the Tevatron (86).

It is perhaps important to mention a particularly useful technique regarding mass reconstruction in the 4τ case. Because $m_a \ll m_h$, the two a decays result in two highly boosted 2τ pairs, and each pair will decay more or less collinearly to the visible 2τ decay products and some missing momentum. In the collinear approximation, there are enough constraint equations to solve for *both* the h and

a masses. In the $WW \rightarrow h$ fusion case, this requires that the h have significant transverse momentum as measured by the recoiling jets. In the $pp \rightarrow pp h$, the forward tagged protons actually provide an over-constrained system even if the h has very little transverse momentum or if this transverse momentum cannot be well measured. For details of the latter see (85).

Another class of possible decays arise when a is fermiophobic to Standard Model fermion decays (33, 51). This possibility does not arise in the NMSSM, but can occur in other models. If a couples to SM-singlet heavy fermions that it cannot decay into, its leading decay is through loop-induced decays into gluons or photons. Thus, the decay modes of the Higgs are into $4g$, $2g\ 2\gamma$, 4γ , in decreasing order of dominance. The four gluon decay suffers from too large of a QCD background to be searched for at the LHC. However, LEP2 constraints on the decays with photons could allow $a \rightarrow \gamma\gamma$ branching ratios as high as 10^{-2} (52); in this case, the subdominant decays might provide a viable LHC signal. In (87), the $2g\ 2\gamma$ decay was analyzed, which showed that, with integrated luminosity of order $300\ \text{fb}^{-1}$, a branching ratio for $h \rightarrow 2g\ 2\gamma$ of a few percent was needed to discover the Higgs and a . In (52), the $h \rightarrow 4\gamma$ decays were analyzed for $300\ \text{fb}^{-1}$. The background was shown to be negligible and a branching ratio of 10^{-4} for $h \rightarrow 4\gamma$ was sufficient to discover both scalars in most of the parameter space. A crucial issue for these fermiophobic decays is efficient triggering. The photons are relatively soft, with $p_T \sim m_h/4$, so passing the di-photon trigger is one of the biggest issues for the signal efficiency. For the 4γ decay, this can be relieved by implementing a multiple photon trigger with a lower threshold than the di-photon trigger.

8.1.2 HIGGS DECAYS WITH DISPLACED VERTICES

In some

cases, the Higgs decays have significantly displaced vertices, which makes LHCb the ideal detector to search for this Higgs. Such Higgs decays have been discussed in supersymmetric models with R-parity violation (88), in hidden valley models (55), and in models with light right-handed neutrinos (62,63). Displaced vertices are possible since the intermediate particle, which facilitates the Higgs cascade decay, can have a suppressed coupling mediating its decay. Decay lengths between $100\,\mu\text{m}$ and $10\,\text{m}$ are the most interesting since they are resolvable within the detector. The LEP2 constraints on such a scenario are difficult to ascertain, especially for highly displaced vertices. However, at any rate, such nonstandard Higgs decays could occur and it is important to determine if there are ways to detect a Higgs decaying in this fashion.

For the case of R-parity violation that is baryon number violating (88), the Higgs decays into a pair of neutralinos which themselves decay into three quarks each. If the neutralino decay is highly displaced, the hadrons formed from the three quarks point back to a vertex. So there is a potential of having two highly displaced vertices that are inconsistent with the Standard Model. Such vertices are easiest to detect and trigger on at LHCb, the dedicated detector for B physics at the LHC. This detector is forward focused and thus non-hermetic, but it is possible for the Higgs to be boosted enough that both neutralino decays occur in the detector. An analysis at LHCb (89) showed that such double displaced vertices have negligible background. Furthermore, such Higgs decays produce 1000's of such double displaced events in a year of LHCb running (integrated luminosity $\sim 2\,\text{fb}^{-1}$), as long as the neutralino mass is not too light. This type of analysis should also apply to other Higgs decays with double displaced

vertices as they are only distinguished by the objects related to each vertex. Those with right-handed neutrinos (62, 63) have dominantly two light quark jets and a charged lepton at a vertex while Hidden Valley models (55) typically have $b\bar{b}$ or $\tau\bar{\tau}$ at each vertex. Thus, depending on whether or not ATLAS/CMS can trigger/isolate such events, it is quite possible that such Higgses will be discovered first at LHCb.

8.1.3 HIGGS DECAYS WITH MISSING ENERGY Recently, Higgs decays that have both missing energy and visible energy have been discussed (34, 62–64). If the Higgs decays into two new neutral particles, one unstable and one stable, the final state will contain both missing and visible energy. There are many potential decay topologies, but the most promising ones for searches have two charged leptons in the final state, giving $l^+l^- \cancel{E}_T$. Depending upon whether or not the Higgs is produced with associated particles, the signal topologies look very similar to standard supersymmetry discovery channels with leptons, for example dilepton and trilepton events with missing energy (34). The resemblance brings up interesting analysis issues. If this Higgs appears in a supersymmetric theory, it will be necessary to produce cuts to isolate the Higgs component from the superpartner production component (for example, see (90)). However, a Higgs decaying in this manner can also appear in a non-supersymmetric theory. These issues suggest that to discover such a Higgs could require cooperation between Higgs and supersymmetry experimentalists — any analysis which yields an unexpected excess or one that is inconsistent with an expected signal should be closely scrutinized.

In these scenarios, the Higgs can also decay invisibly into some combination of neutrinos and other stable particles. Searches for such invisible Higgs decays

are already planned for the LHC, where it has been shown that relatively small values (perhaps as small as 5 – 10%) for $\text{Br}(h \rightarrow \cancel{E}_T)$ can yield a viable signal in the WW -fusion production mode, assuming SM-like hWW coupling (91,92). In (93), the potential of using this channel alone to discover the Higgs was studied in several extended supersymmetric Standard Models. The $pp \rightarrow pp h \rightarrow pp \cancel{E}_T$ forward diffractive production channel is also expected to yield a viable signal at full 300 fb^{-1} integrated luminosity for $\text{Br}(h \rightarrow \cancel{E}_T)$ significantly below 1 (94). Generically speaking, Higgs decays containing missing energy can appear in several channels. Hopefully, some combination of these searches (and potentially combined with the Standard Model searches) can make possible the discovery of such a Higgs.

8.2 Supersymmetric Particle Searches

Aside from changes in Higgs phenomenology, there are important implications of nonstandard Higgs models for other sectors of the theory. First, we have seen that in order to avoid fine-tuning, low masses for the superpartners (in particular for the stop and the gluino) are required, typically just beyond current Tevatron limits. For the required masses, production rates of superpartners at the LHC will be very large. Supersymmetry will be discovered with relatively little integrated luminosity, whereas Higgs discovery will require large integrated luminosity and will therefore take more time. Thus, the LHC experimental collaborations should be on the watch for a situation in which they have discovered supersymmetry but have not seen any of the Higgs signals in the MSSM for the expected amounts of integrated luminosity. Higgs channels with cascade decays should then become a high priority. In addition, it will be important to determine whether WW

scattering is, or is not, perturbative in nature. If it is perturbative, then it is necessary for there to be one or more relatively light (below 300 GeV) Higgs boson with large WW coupling that must be searched for.

Implications for BSM particle searches are of even greater importance in models where the Higgs decays into particles that transform under a new symmetry. In supersymmetric models, this symmetry is R -parity. Supersymmetric particles, being odd under R -parity, have to cascade decay down into the lightest particle that is R -parity odd, aka the lightest supersymmetric particle (LSP). When the (SM-like) Higgs decays into supersymmetric particles, these will typically be the lighter supersymmetric particles. The branching ratio for such decays will often determine or at least constrain the properties of the light supersymmetric particles, which in turn constrains how the heavier supersymmetric particles cascade down to the LSP.

The simplest possibility, where the light (≤ 100 GeV) Higgs decays into two LSPs, is not allowed (without R -parity violation) since the decay is invisible and ruled out by the LEP invisible Higgs search. The next simplest possibility is for the Higgs to decay into the LSP and a heavier supersymmetric particle. Both particles are neutral and the heavier one is unstable, decaying down into the LSP. This gives a missing and visible energy component to the Higgs decay, which was discussed earlier in Section 8.1.3.

In supersymmetric theories, this nonstandard decay can be into neutralinos or sneutrinos. For neutralinos, requiring the Higgs to decay into $\tilde{\chi}_1\tilde{\chi}_0$ and imposing the constraints on charginos and neutralinos specifies the neutralino spectrum. This requires an NMSSM-like supersymmetric theory where the LSP $\tilde{\chi}_0$ is mostly singlino in gauge eigenstate composition, while $\tilde{\chi}_1$ is mostly bino (as verified

via a scan using NMHDECAY (71); see also (95)). Thus, the LSP has very weak couplings mostly mediated through the superpotential interaction $\hat{S}\hat{H}_u\hat{H}_d$. In terms of the cascade decays of supersymmetric particles, this has a drastic consequence. Their cascades get lengthened, as they will dominantly cascade first to $\tilde{\chi}_1$ which will then decay down to $\tilde{\chi}_0$. Thus, at first order, the supersymmetric cascades are as in the MSSM, followed by a final decay down of the binos into a lighter neutralino. NMSSM-like models with an extra $U(1)$ and several extra Higgs fields transforming differently under the extra $U(1)$ can lead to a complex scenario for Higgs decays and supersymmetric cascades (68). If such a model is realized in nature, it could take decades to sort out this physics.

For now, we focus on the less complex nonstandard decay cascades. Even these have important consequences for collider searches (96,97). At the Tevatron and LEP, searches for squarks and staus will have weaker constraints due to these decays (98). At the LHC, most cascades of superpartner decays will include the characteristic decay of $\tilde{\chi}_1$ to $\tilde{\chi}_0$. Furthermore, since the $\tilde{\chi}_1$ and $\tilde{\chi}_0$ must be light in order to appear in the Higgs decay, their production cross sections (at least that for $\tilde{\chi}_1\tilde{\chi}_1$) at the LHC will be large. Most probably, other superpartner particles will also be relatively light. In this case, supersymmetry will be discovered with an early amount of luminosity ($\sim 30 \text{ fb}^{-1}$), while the Higgs, because of its nonstandard decays, will not have been discovered. By analyzing the supersymmetry events, it may be possible to measure the branching ratios of the decays of $\tilde{\chi}_1$ to $\tilde{\chi}_0$ and some of the properties of the $\tilde{\chi}_1$ and $\tilde{\chi}_0$. This will help determine whether the Higgs will have a large $\text{Br}(h \rightarrow \tilde{\chi}_1\tilde{\chi}_0)$ and provide crucial information regarding the nonstandard decay topology of the SM-like Higgs. This information can then be used to design searches to pick out this decay in the

design luminosity run of the LHC.

In the cascade decay scenario where the neutralino decays via R -parity violation with a displaced vertex (88), LHCb's capabilities make it possible to efficiently search for such vertices. In (89), the production of a squark decaying into the lightest neutralino was considered. Compared to the Higgs signal, it is less likely for two squarks to appear in LHCb. Still, there is a reasonable region of parameter space that allows the discovery of the squark at LHCb, via the appearance of one such displaced vertex within one year of running. Thus, it is possible that LHCb will discover both the Higgs and supersymmetry before ATLAS/CMS.

9 CONCLUSION

The motivations for a light (≤ 100 GeV) Higgs boson with SM-like couplings to SM particles, but with dominant decays to non-SM particles, are very substantial. Typically, and explicitly in the NMSSM, fine-tuning can be minimized and/or eliminated if the Higgs is this light. In addition, a Higgs mass below 100 GeV is most consistent with precision electroweak data. Furthermore, because of the very small $h \rightarrow SM$ decay widths for a light h , the $h \rightarrow SM$ branching ratios are easily greatly suppressed by the presence of couplings to a pair of particles (with summed mass below m_h) from a nonstandard sector. Dominance of nonstandard decays typically imply that LEP limits on m_h are reduced to below roughly 90 GeV so long as the ultimate final state is not $h \rightarrow 4b$ (for which LEP requires $m_h > 110$ GeV). And, in many cases the $h \rightarrow b\bar{b}$ branching ratio is reduced to the $\sim 10\%$ level that would explain the excess in $Z + b\bar{b}$ seen at $M_{b\bar{b}} \sim 98$ GeV at LEP.

The NMSSM scenarios with no fine-tunings, where the lightest CP-even Higgs,

h_1 , has $m_{h_1} \sim 100$ GeV and is SM-like in its couplings to SM particles but decays via $h_1 \rightarrow a_1 a_1 \rightarrow 4\tau$ or (less likely, $4j$) and/or $h_1 \rightarrow \tilde{\chi}_1 \tilde{\chi}_0 \rightarrow f\bar{f} + \cancel{E}_T$, deserve particular attention. In the NMSSM, to have low fine-tuning the stop and gluino should be just above Tevatron limits and easily discoverable at the LHC. If $h_1 \rightarrow \tilde{\chi}_1 \tilde{\chi}_0$, $m_{\tilde{\chi}_1} + m_{\tilde{\chi}_0} < m_{h_1}$ implies $\tilde{\chi}_1 \tilde{\chi}_1$ detection may also be possible early on. But, Higgs discovery will be challenging in all these cases. If supersymmetric particle decays indicate that R -parity is violated baryonically, then one should also be alert to the possibility that $h_1 \rightarrow \tilde{\chi}_0 \tilde{\chi}_0 \rightarrow 6j$ decays could be dominant. This kind of mode can be present in the MSSM as well as the NMSSM. If one is willing to accept a significant but not outrageous 6% fine tuning, many more Higgs scenarios emerge. For example, in the NMSSM the $h_1 \rightarrow a_1 a_1 \rightarrow 4b$ and $2b + 2\tau$ channels with $m_{h_1} > 110$ GeV (from LEP limits) would provide possible discovery modes.

To summarize, the allowed nonstandard Higgs decay topologies are of a few limited types. There are decays into four SM fermions, which are often mediated by a scalar ϕ , giving $h \rightarrow 2\phi \rightarrow 4f$. Heavier fermions f are usually favored, although the strong limits on $4b$ decays suggest that ϕ is lighter than the $b\bar{b}$ threshold so that the dominant decay is into 4τ 's. If the scalar ϕ is fermiophobic, loop-induced decays can generate the decay $h \rightarrow 2\phi \rightarrow 4V$, where V is a photon or gluon. When there are more than one new state into which the Higgs can decay, it opens up the possibility of one of these states being stable. Thus, there can be decays with both missing and visible energy, usually of the type $h \rightarrow (X_2)X_1 \rightarrow (f\bar{f}X_1)X_1 = f\bar{f} + \cancel{E}$. In addition, there is the potential of displaced vertices, when the decay ϕ or X_2 are long lived. These vertices could give LHCb an inside track on finding such Higgs decays. Finally, adding additional particles

can make the Higgs cascade decay longer and more complex. In some cases, input from B factories and/or non-Higgs LHC searches can pin down some properties of these intermediate states appearing in the Higgs cascade. Thus, if no SM Higgs has been found at the LHC at the expected integrated luminosity, it will be advantageous to use all available information about these new states to design efficient searches for the nonstandard Higgs decays.

In general, Higgs decays and phenomenology provide an unexpectedly fertile probe of and window to physics beyond the Standard Model and potentially beyond the minimal supersymmetric model. Nonstandard decays are a double-edged sword, on the one hand possibly making Higgs detection at the LHC much more difficult while on the other hand providing information regarding a new sector of the theory. The additional particles from the beyond the SM or beyond the MSSM sector could have very weak direct production cross sections at the LHC and might only be observed via Higgs decays. Apart from any other consideration, a highly detailed understanding and delineation of all Higgs decays will be crucial to understanding BSM physics. We must hope that the LHC will prove up to the task, but cannot rule out the possibility that a linear collider will ultimately be necessary — at the very least it would greatly refine the LHC observations.

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LITERATURE CITED

1. L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999), hep-ph/9905221.
2. M. Schmaltz and D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. **55**, 229 (2005), hep-ph/0502182.
3. M. Perelstein, Prog. Part. Nucl. Phys. **58**, 247 (2007), hep-ph/0512128.
4. R. Barbieri and A. Strumia, (2000), hep-ph/0007265.
5. Particle Data Group, W. M. Yao *et al.*, J. Phys. **G33**, 1 (2006).
6. R. Dermisek and J. F. Gunion, Phys. Rev. Lett. **95**, 041801 (2005), hep-ph/0502105.
7. LEP-EWWG, <http://www.cern.ch/LEPEWWG>.
8. M. S. Chanowitz, Phys. Rev. **D66**, 073002 (2002), hep-ph/0207123.
9. A. Ferrogia, G. Ossola, and A. Sirlin, (2004), hep-ph/0406334.
10. LEP Working Group for Higgs boson searches, R. Barate *et al.*, Phys. Lett. **B565**, 61 (2003), hep-ex/0306033.
11. M. Drees, Phys. Rev. **D71**, 115006 (2005), hep-ph/0502075.
12. R. Dermisek and J. F. Gunion, (2007), arXiv:0709.2269 [hep-ph].
13. J. F. Gunion and H. E. Haber, Nucl. Phys. **B272**, 1 (1986).
14. L.-F. Li, Y. Liu, and L. Wolfenstein, Phys. Lett. **B159**, 45 (1985).
15. J. F. Gunion and H. E. Haber, Nucl. Phys. **B278**, 449 (1986).
16. A. Djouadi, J. Kalinowski, and M. Spira, Comput. Phys. Commun. **108**, 56 (1998), hep-ph/9704448.
17. J. F. Gunion and H. E. Haber, Nucl. Phys. **B307**, 445 (1988).
18. J. F. Gunion, L. Roszkowski, and H. E. Haber, Phys. Rev. **D38**, 105 (1988).
19. J. R. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski, and F. Zwirner, Phys.

- Rev. **D39**, 844 (1989).
20. J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, Perseus Publishing, Cambridge, MA, 1990.
21. J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, (1992), hep-ph/9302272.
22. J. R. Espinosa and J. F. Gunion, Phys. Rev. Lett. **82**, 1084 (1999), hep-ph/9807275.
23. T. Binoth and J. J. van der Bij, Z. Phys. **C75**, 17 (1997), hep-ph/9608245.
24. LEP Higgs Working Group for Higgs boson searches, (2001), hep-ex/0107034.
25. LEP, A. Rosca, (2002), hep-ex/0212038.
26. LEP Higgs Working Group for Higgs boson searches, (2001), hep-ex/0107032.
27. OPAL, G. Abbiendi *et al.*, Eur. Phys. J. **C37**, 49 (2004), hep-ex/0406057.
28. DELPHI, J. Abdallah *et al.*, Eur. Phys. J. **C38**, 1 (2004), hep-ex/0410017.
29. ALEPH, S. Schael *et al.*, Eur. Phys. J. **C47**, 547 (2006), hep-ex/0602042.
30. OPAL, G. Abbiendi *et al.*, Eur. Phys. J. **C27**, 483 (2003), hep-ex/0209068.
31. OPAL, G. Abbiendi *et al.*, Eur. Phys. J. **C27**, 311 (2003), hep-ex/0206022.
32. ALEPH, J. Alcaraz *et al.*, (2006), hep-ex/0612034.
33. S. Chang, P. J. Fox, and N. Weiner, JHEP **08**, 068 (2006), hep-ph/0511250.
34. S. Chang and N. Weiner, (2007), arXiv:0710.4591 [hep-ph].
35. Y. Okada, M. Yamaguchi, and T. Yanagida, Prog. Theor. Phys. **85**, 1 (1991).
36. H. E. Haber and R. Hempfling, Phys. Rev. Lett. **66**, 1815 (1991).
37. J. R. Ellis, G. Ridolfi, and F. Zwirner, Phys. Lett. **B257**, 83 (1991).
38. J. R. Ellis, G. Ridolfi, and F. Zwirner, Phys. Lett. **B262**, 477 (1991).
39. R. Dermisek and H. D. Kim, Phys. Rev. Lett. **96**, 211803 (2006), hep-ph/0601036.

- 40. R. Dermisek and J. F. Gunion, Phys. Rev. **D76**, 095006 (2007), arXiv:0705.4387 [hep-ph].
- 41. A. Brignole, J. A. Casas, J. R. Espinosa, and I. Navarro, Nucl. Phys. **B666**, 105 (2003), hep-ph/0301121.
- 42. M. Dine, N. Seiberg, and S. Thomas, Phys. Rev. **D76**, 095004 (2007), arXiv:0707.0005 [hep-ph].
- 43. R. Barbieri, L. J. Hall, A. Y. Papaioannou, D. Pappadopulo, and V. S. Rychkov, (2007), arXiv:0712.2903 [hep-ph].
- 44. P. C. Schuster and N. Toro, (2005), hep-ph/0512189.
- 45. R. Dermisek and J. F. Gunion, Phys. Rev. **D75**, 075019 (2007), hep-ph/0611142.
- 46. D. A. Demir, L. Solmaz, and S. Solmaz, Phys. Rev. **D73**, 016001 (2006), hep-ph/0512134.
- 47. R. Dermisek and J. F. Gunion, Phys. Rev. **D73**, 111701 (2006), hep-ph/0510322.
- 48. M. S. Carena, J. R. Ellis, A. Pilaftsis, and C. E. M. Wagner, Phys. Lett. **B495**, 155 (2000), hep-ph/0009212.
- 49. D. Kreinick, (2007), arXiv:0710.5929 [hep-ex].
- 50. A. Delgado, J. R. Espinosa, and M. Quiros, JHEP **10**, 094 (2007), arXiv:0707.4309 [hep-ph].
- 51. B. A. Dobrescu, G. L. Landsberg, and K. T. Matchev, Phys. Rev. **D63**, 075003 (2001), hep-ph/0005308.
- 52. S. Chang, P. J. Fox, and N. Weiner, Phys. Rev. Lett. **98**, 111802 (2007), hep-ph/0608310.
- 53. A. Arhrib, K. Cheung, T.-J. Hou, and K.-W. Song, JHEP **03**, 073 (2007),

- hep-ph/0606114.
54. M. J. Strassler and K. M. Zurek, Phys. Lett. **B651**, 374 (2007), hep-ph/0604261.
55. M. J. Strassler and K. M. Zurek, (2006), hep-ph/0605193.
56. D. O’Connell, M. J. Ramsey-Musolf, and M. B. Wise, Phys. Rev. **D75**, 037701 (2007), hep-ph/0611014.
57. S. G. Kim *et al.*, Phys. Rev. **D74**, 115016 (2006), hep-ph/0609076.
58. B. Patt and F. Wilczek, (2006), hep-ph/0605188.
59. O. Bahat-Treidel, Y. Grossman, and Y. Rozen, JHEP **05**, 022 (2007), hep-ph/0611162.
60. R. N. Hodgkinson and A. Pilaftsis, Phys. Rev. **D76**, 015007 (2007), hep-ph/0612188.
61. S. Gopalakrishna, S. Jung, and J. D. Wells, (2008), arXiv:0801.3456 [hep-ph].
62. M. L. Graesser, (2007), arXiv:0705.2190 [hep-ph].
63. M. L. Graesser, Phys. Rev. **D76**, 075006 (2007), arXiv:0704.0438 [hep-ph].
64. A. de Gouvea, (2007), arXiv:0706.1732 [hep-ph].
65. R. Apreda, M. Maggiore, A. Nicolis, and A. Riotto, Class. Quant. Grav. **18**, L155 (2001), hep-ph/0102140.
66. A. Menon, D. E. Morrissey, and C. E. M. Wagner, Phys. Rev. **D70**, 035005 (2004), hep-ph/0404184.
67. S. Profumo, M. J. Ramsey-Musolf, and G. Shaughnessy, JHEP **08**, 010 (2007), arXiv:0705.2425 [hep-ph].
68. T. Han, P. Langacker, and B. McElrath, Phys. Rev. **D70**, 115006 (2004), hep-ph/0405244.
69. V. Barger, P. Langacker, H.-S. Lee, and G. Shaughnessy, Phys. Rev. **D73**,

- 115010 (2006), hep-ph/0603247.
70. V. Barger, P. Langacker, M. McCaskey, M. J. Ramsey-Musolf, and G. Shaughnessy, (2007), arXiv:0706.4311 [hep-ph].
71. U. Ellwanger, J. F. Gunion, and C. Hugonie, *JHEP* **02**, 066 (2005), hep-ph/0406215.
72. J. F. Gunion, H. E. Haber, and T. Moroi, (1996), hep-ph/9610337.
73. R. Dermisek, J. F. Gunion, and B. McElrath, *Phys. Rev.* **D76**, 051105 (2007), hep-ph/0612031.
74. E. Fullana and M.-A. Sanchis-Lozano, *Phys. Lett.* **B653**, 67 (2007), hep-ph/0702190.
75. C. P. Burgess, J. Matias, and M. Pospelov, *Int. J. Mod. Phys.* **A17**, 1841 (2002), hep-ph/9912459.
76. CMS Collaboration, TDR Volume II, *Journal of Physics G Nuclear Physics* **34**, 995 (2007).
77. K.-m. Cheung, J. Song, and Q.-S. Yan, (2007), arXiv:0710.1997 [hep-ph].
78. M. Carena, T. Han, G.-Y. Huang, and C. E. M. Wagner, (2007), arXiv:0712.2466 [hep-ph].
79. U. Ellwanger, J. F. Gunion, and C. Hugonie, *JHEP* **07**, 041 (2005), hep-ph/0503203.
80. U. Ellwanger, J. F. Gunion, C. Hugonie, and S. Moretti, (2004), hep-ph/0401228.
81. U. Ellwanger, J. F. Gunion, C. Hugonie, and S. Moretti, (2003), hep-ph/0305109.
82. S. Moretti, S. Munir, and P. Poulose, *Phys. Lett.* **B644**, 241 (2007), hep-ph/0608233.

- 83. T. Stelzer, S. Wiesenfeldt, and S. Willenbrock, *Phys. Rev.* **D75**, 077701 (2007), hep-ph/0611242.
- 84. K. Cheung, J. Song, and Q.-S. Yan, *Phys. Rev. Lett.* **99**, 031801 (2007), hep-ph/0703149.
- 85. J. R. Forshaw, J. F. Gunion, L. Hodgkinson, A. Papaefstathiou, and A. D. Pilkington, (2007), arXiv:0712.3510 [hep-ph].
- 86. P. W. Graham, A. Pierce, and J. G. Wacker, (2006), hep-ph/0605162.
- 87. A. Martin, (2007), hep-ph/0703247.
- 88. L. M. Carpenter, D. E. Kaplan, and E.-J. Rhee, (2006), hep-ph/0607204.
- 89. D. E. Kaplan and K. Rehermann, *JHEP* **10**, 056 (2007), arXiv:0705.3426 [hep-ph].
- 90. H. Baer, M. Bisset, D. Dicus, C. Kao, and X. Tata, *Phys. Rev.* **D47**, 1062 (1993).
- 91. O. J. P. Eboli and D. Zeppenfeld, *Phys. Lett.* **B495**, 147 (2000), hep-ph/0009158.
- 92. B. Di Girolamo, A. Nikitenko, L. Neukermans, K. Mazumdar, and D. Zeppenfeld, Prepared for Workshop on Physics at TeV Colliders, Les Houches, France, 21 May - 1 Jun 2001.
- 93. V. Barger, P. Langacker, and G. Shaughnessy, *Phys. Rev.* **D75**, 055013 (2007), hep-ph/0611239.
- 94. K. Belotsky, V. A. Khoze, A. D. Martin, and M. G. Ryskin, *Eur. Phys. J.* **C36**, 503 (2004), hep-ph/0406037.
- 95. V. Barger, P. Langacker, and G. Shaughnessy, *Phys. Lett.* **B644**, 361 (2007), hep-ph/0609068.
- 96. M. J. Strassler, (2006), hep-ph/0607160.

- 97. U. Ellwanger and C. Hugonie, Eur. Phys. J. **C13**, 681 (2000), hep-ph/9812427.
- 98. S. Chang, D. Tucker-Smith, and N. Weiner, (2007), work in progress.